# INK JET RECORDING HEAD HAVING REDUCED STRESS CONCENTRATION NEAR THE BOUNDARIES OF PRESSURE GENERATING CHAMBERS

## BACKGROUND OF THE INVENTION

The present invention relates to an ink-jet recording head having piezoelectric layers formed on a surface of an elastic sheet which forms part of pressure generating chambers communicating with nozzle orifices from which ink drops are allowed to issue by displacement of the piezoelectric layers.

The operating principle of ink-jet recording heads is such that the elastic sheet described above is displaced by means of piezoelectric vibrators to apply pressure to the ink in pressure generating chambers, thereby ejecting ink drops from nozzle orifices. Practically, ink-jet recording heads are classified as one of two types depending on the piezoelectric vibrator used; one type uses a vibrator of a longitudinally vibrating mode which extends and contracts along its own axis and the other type uses a vibrator of a flexing or flexural vibrating mode.

The first type of ink-jet recording heads is capable of changing the volume of each pressure generating chamber by contacting an end face of the piezoelectric vibrator with the elastic sheet and has the advantage of being suitable for high-density printing. On the other hand, the manufacturing process of this type of head is complicated since it involves not only a difficult step of segmenting the piezoelectric elastic sheet into a combtooth-shaped pattern in registry with the pitch on which nozzle orifices are arranged but also the step of fixing the individual piezoelectric vibrators in an appropriate positional relationship with the respective pressure generating chambers.

In contrast, the second type of ink-jet recording heads has the advantage of enabling the piezoelectric vibrators to be mounted on the elastic sheet by a relatively simple process in which a green sheet of piezoelectric material is attached to a substrate is conformity with the shape of individual pressure generating chambers and baked. On the other hand, a certain area is required to permit flexural vibrations and this introduces difficulty in achieving high-density arrangement of piezoelectric vibrators.

To deal with these problems, it has been proposed as in Unexamined Published Japanese Patent Application No. Hei. 5-286131 that a uniform layer of piezoelectric material be formed over the entire surface of the elastic sheet by film deposition techniques and that the formed piezoelectric layer be segmented into shapes that correspond to the pressure generating chambers by lithographic techniques such that the piezoelectric vibrator formed in one pressure generating chamber is independent of the vibrator formed in another pressure generating chamber.

This proposal eliminates the need to attach the piezoelectric vibrators onto the elastic sheet and offers the advantage of not only enabling the piezoelectric vibrators to be mounted by the precise and yet simple lithographic techniques but also reducing the thickness of each piezoelectric vibrator by a sufficient amount to permit fast driving.

On the other hand, the piezoelectric layer is so thin that compared to the attached type of piezoelectric vibrator, the rigidity is small enough to increase the chance of stress concentration near the boundaries of each pressure generating chamber and this causes the disadvantage of shortening the life of the elastic sheet, piezoelectric vibrators and even the electrodes.



As another problem, the piezoelectric constant is only about a third to half of the value for the piezoelectric vibrator that is formed by baking an attached green sheet and this requires driving at high voltage; then, both the upper and lower electrodes will experience surface discharge along the lateral sides of the piezoelectric layer which increases the chance of a leakage current of flowing between the two electrodes, thereby destabilizing the issuance of ink droplets. A further problem is that if the piezoelectric vibrator is segmented or divided in correspondence with individual pressure generating chambers, the areas of lateral sides that are exposed to air atmosphere are increased so that the individual piezoelectric vibrators are prone to deteriorate due to the moisture in air atmosphere.

## SUMMARY OF THE INVENTION

The present invention has been accomplished under these circumstances and has as an object providing an ink-jet recording head in which the stress concentration near the boundaries of each pressure generating chamber is sufficiently reduced to prevent the breakage of the upper electrode.

Another object of the invention is to provide an ink-jet recording head which, in addition to the stated advantage, is capable of preventing not only the occurrence of a leakage current through the piezoelectric layer held between the upper and lower electrodes to thereby stabilize the issuance of ink droplets, but also the deterioration of piezoelectric vibrators.

According to a first aspect of the invention, there is provided an ink-jet recording head comprising: an elastic sheet providing pressure generating chambers; nozzle orifices, each communicating with the pressure generating chamber; piezoelectric vibrators formed on the elastic sheet, each of the piezoelectric vibrators having, a lower electrode formed on the elastic sheet, a piezoelectric layer formed on the lower electrode, and an upper electrode formed on the piezoelectric layer such that the upper electrode faces the respective pressure generating chamber, wherein the upper electrodes of the piezoelectric vibrators are positioned independently of each other, an electrical insulator layer having windows, wherein the electrical insulator layer covers the upper electrodes; and a conductor pattern connecting with the upper electrodes via the windows of the electrical insulator layer.

Therefore, the upper electrodes are situated inward of the pressure generating chambers, so they will not experience any abrupt displacements at the boundaries of the pressure generating chambers and hence are damage-free.

According to a second aspect of the invention, there is provided an ink-jet recording head comprising: an elastic sheet providing pressure generating chambers; nozzle orifices, each communicating with the pressure generating chamber; piezoelectric vibrators formed on the elastic sheet, each of the piezoelectric vibrators having, a lower electrode formed on the elastic sheet, a piezoelectric layer formed on the lower electrode, and an upper electrode formed on the piezoelectric layer such that the upper electrode faces the respective pressure generating chamber, wherein the piezoelectric layer and the upper electrodes are formed inside of the areas facing the respective pressure generating chamber; an electrical insulator layer having windows, wherein the electrical insulator layer covers the upper electrodes, and a conductor pattern connecting with the upper electrodes via the windows of the electrical insulator layer.

The second aspect is effective not only in preventing the stress concentration due to the abrupt displacement at the

boundaries of each of the pressure generating chambers, but also in ensuring good electrical insulation between the upper and lower electrodes and complete isolation from air atmosphere by means of the electrical insulator layer.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded perspective view of an ink-jet recording head according to an embodiment of the invention;

FIG. 2A shows the structure of a longitudinal section of a single pressure generating chamber in the ink-jet recording head;

FIG. 2B shows the layout of conductor patterns with particular reference to the relative positions of pressure generating chambers, upper electrodes and a lower electrode;

FIG. 3A shows the structure of a longitudinal section of a single pressure generating chamber in an ink-jet recording head according to another embodiment of the invention;

FIG. 3B shows the layout of conductor patterns with reference to the relative positions of pressure generating chambers, upper electrodes and a lower electrode;

FIG. 4A shows the structure of a longitudinal section of a pressure generating chamber in an ink-jet recording head according to yet another embodiment of the invention;

FIG. 4B shows the structure of two pressure generating chambers in a section that is taken in a direction in which they are oriented side by side;

FIGS. 5-I to 5-II' show the second half of a method of processing a single-crystal silicon substrate to fabricate the ink-jet recording head of the invention;

FIGS. 6-I to 6-II' show the second half of the processing method;

FIG. 7 is a longitudinal section of another type of ink-jet recording head to which the electrode structure of the invention is applicable in accordance with a further embodiment of the invention; and

FIG. 8 is a longitudinal section of an exemplary ink-jet recording head that employs flexing vibrators.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will now be described in detail with reference to the embodiments shown in accompanying drawings.

FIG. 1 is an exploded perspective view of an embodiment of the invention and FIGS. 2A and 2B show the structure of a section of one pressure generating chamber as taken in the longitudinal direction. In these figures, numeral 1 refers to an ink channel forming substrate which is open on one side and provided on the other side with an elastic sheet 2 of silicon oxide. The substrate 1 is a single-crystal silicon substrate which is etched anisotropically to from pressure generating chambers 3 and reservoirs 4, as well as ink supply ports 5 in the form of recesses that communicate with the pressure generating chambers 3 and reservoirs 4 through a certain resistance to fluid flow.

Those areas of the elastic sheet 2 which face the individual pressure generating chambers 3 are provided with piezoelectric vibrators 6 that are mounted independently of each other by a film deposition technique in the respective generating pressure chambers 3

Each piezoelectric vibrator 6 comprises in superposition of a lower electrode **10** formed on a surface of the elastic sheet **2** to cover the substantial areas of each pressure generating compartment **3** and each ink supply port **5**, a piezoelectric layer **11** formed in such a way that it does not extend beyond the area of the pressure generating chamber **3** in which the elastic sheet **2** is exposed and such that it is slightly narrower than the width of the pressure generating chamber **3**, and an upper electrode **12** formed on a surface of each piezoelectric layer **11**.

As shown clearly in FIGS. **2A** and **2B**, the piezoelectric layers **11** and upper electrodes **12** are each formed in such a way that the sides **11*a*** and **12*a*** on the nozzle orifice side and the sides **11*b*** and **12*b*** on the ink supply port side are each located inward of the boundaries **3*a*** and **3*b*** of the pressure generating chamber **3** in a longitudinal direction and desirably inward of the partition walls of each pressure generating chamber in the direction of width.

A thin electrical insulator layer **13** is formed to cover at least the peripheral edge of the top surface of the upper electrode **12** and the lateral sides of the piezoelectric layer **11**. The insulator layer **13** is formed of any material that permits film formation by a suitable deposition technique or which can be trimmed by etching as exemplified by silicon oxide, silicon nitride or an organic material, preferably a photosensitive polyimide having low rigidity and good electrical insulating property.

A window **13*a*** is formed in a selected area of the upper electrode **12** on the insulator layer **13** to have the upper electrode **12** partly exposed to establish connection to a conductor pattern **14**. One end of the conductor pattern **14** is connected to the upper electrode **12** via the window **13*a*** and the other end extends to a suitable connection terminal. The conductor pattern **14** is formed in the smallest possible width that ensures positive supply of a drive signal to the upper electrode **12**.

Shown by **15** is a nozzle plate with nozzle orifices **16** that communicate with the pressure generating chambers **3** at one end; the nozzle plate **15** is fixed in such a way as to close the open side of the ink channel forming substrate **1**. Shown by **17** in FIG. **1** is a flexible cable for supplying a drive signal to the piezoelectric vibrators **6** and numeral **18** designates a head case.

In the embodiment under discussion, a drive signal supplied from an external drive circuit to each piezoelectric vibrator **6** via the flexible cable **17** passes through the conductor pattern **14** to be applied to the upper electrode **12**, whereupon the piezoelectric vibrator **6** flexes to reduce the volume of the pressure generating chamber **3**

As a result of this volume change, the ink in the pressure generating chamber **3** is given a sufficient pressure to be partly ejected as an ink drop from the nozzle orifice **16**. When the issuance of the ink drop ends, the piezoelectric vibrator **6** reverts to the initial sate, whereupon the volume of the pressure generating chamber **3** increases to allow the ink in the reservoir **4** to flow into the pressure generating chamber **3** via the ink supply port **5**.

As already mentioned, the piezoelectric layer **11**, which is a component of each piezoelectric vibrator **6**, is formed in such a size that the two ends **11*a*** and **11*b*** are located inward of the boundaries **3*a*** and **3*b*** of the pressure generating chamber **3**. In other words, no part of the piezoelectric layer **11** or the upper electrode **12** is positioned at the boundary **3*b*** and subject to the effect of a sharp displacement gradient Hence, the piezoelectric layers **11** and the upper electrodes **12** are entirely free from breaking due to mechanical fatigue.

FIG **8** shows a conventional type of ink-jet recording head in which a piezoelectric layer **11'** extends near to an end

portion of the head to serve as an insulator layer between the lower electrode **10** and an upper electrode **12'**, of which an extension is used as a lead-out electrode. In this case, the piezoelectric layer **11'** is located at the end **3b** of the pressure generating chamber **3** and a sharp displacement gradient will occur in the area of the piezoelectric layer **11'** which faces the boundary **3b** to thereby increase the chance of the piezoelectric vibrator **6** of breaking.

Returning back to the invention, the conductor pattern **14** connected to the upper electrode **12** is formed on a surface of the insulator layer **13** and has a sufficient spacing from the lower electrode **10** to provide the necessary insulation resistance for preventing surface discharge; in addition, the static capacity and the piezoelectric loss are reduced to such low levels that one can avoid the drop in response speed and prevent heat generation.

Further in addition, the piezoelectric layer **11**, which will readily change in piezoelectric constant and other characteristics upon moisture absorption has the top surface isolated from air atmosphere by means of the upper electrode **12** and the insulator layer **13**, which are both formed of a dense film, whereas the lateral sides of the piezoelectric layer **11** are isolated from air atmosphere by means of the insulator layer **13**. Therefore, the piezoelectric layer **11** will not absorb moisture but can maintain its initial characteristics for a prolonged time.

In the embodiment described above, the conductor pattern **14** is connected to only one end of the upper electrode **12**. This is not the sole case of the invention and, as shown in FIGS. **3A** and **3B**, the conductor pattern **14** may extend to a lateral side of the upper electrode **12** and a plurality of windows **13a**, **13b** and **13c** are formed in the insulator layer **13** facing the upper electrodes **12**, such that the conductor pattern **14** is connected to the upper electrode **12** via these windows **13a** to **13c**. This design is effective in supplying a drive signal to the upper electrode **12** with the smallest possible response delay.

In the embodiment shown described above, windows **13a**, **13b** and **13c** are formed in the insulator layer **13** in conformity with the shape of the connections to the conductor pattern **14** Alternatively, windows larger than the connections to the conductor pattern **14** may be formed in the insulator layer **13** in all areas except selected portions ΔL, ΔL' and ΔL" of the periphery of the top surface of the upper electrode as shown in FIGS. 4A and 4B. Even in this case, the piezoelectric layer **11** has its surface covered with the upper electrode **12** which is formed of a dense film of platinum or any other suitable metal whereas the lateral sides of the piezoelectric layer **11** are covered with the insulator layer **13** such that the piezoelectric layer **11** is entirely isolated from air atmosphere to prevent the deterioration by atmospheric moisture or the like and the surface discharge occurring along the lateral sides.

The windows in the insulator layer occupy the greater part of the displacement region of the piezoelectric layer **11** and only the upper electrode **12** is superposed on that region of the piezoelectric layer **11**; as a result, the increase in rigidity due to the rigidity of the insulator layer **13** is minimized to permit the piezoelectric layer **11** to be displaced by a greater amount per unit voltage than in the previous embodiments.

The recording heads of the types described above can basically be fabricated by anisotropic etching of a single-crystal silicon substrate used as a preform and processed as described below with reference to FIGS. **5** and **6**.

First, the opposite surfaces of the single-crystal silicon substrate **20** are thermally oxidized or otherwise processed



to form silicon oxide films **21** and **22**. A conductive layer **23** working both as a diaphragm and as a lower electrode is formed by sputtering Pt on one side of the substrate to prepare a preform. A piezoelectric layer **24** typically made of PZT (lead zirconate-titanate) is formed on a surface of the conductive layer **23** and a conductive layer is also formed as an upper electrode successively. In the next step, both the upper electrode and the piezoelectric layer are etched successively by a photo-lithographic technique in conformity with the shape of the pressure generating chambers Subsequently, the lower electrode is patterned by a photo-lithographic technique. Further in addition, the silicon oxide film **22** on the other side of the single-crystal silicon substrate **20** is patterned by a photo-lithographic technique in conformity with the shape of the pressure generating chambers. Hydrofluoric acid is used as an etchant to etch the silicon oxide film **22** during the patterning process and the piezoelectric layer **24** can effectively be protected from the hydrofluoric acid by simply coating a resist on the layer (FIG. 5-I).

In the next step, a fluoroplastic protective film **26** is formed in a thickness of about 6 μm over the piezoelectric layer **24** and the conductive layers **23** and **25** (FIG. **5-II**).

A suitable fluoroplastic resin is whirl coated in a thickness of about 2 μm and dried by heating at 120° C. for 20 min. By repeating these procedures three times, the desired protective film **26** can be formed in intimate contact with the piezoelectric layer **24** and the conductive layers **23** and **25** with the degree of polymerization being adequately increased.

Another method of forming the fluoroplastic protective film **26** is shown in FIG. **5-II'**. A suitable resin film **27** is attached to the other side of the preform and the entire assembly is immersed in a fluoroplastic resin solution such that the latter is deposited to cover the piezoelectric layer **24** and the conductive layers **23** and **25**. The deposited fluoroplastic coating **28** is preannealed at 100° C. for about **30** min, then heated at 200° C. for 30 min until the coating **28** cures to such a hardness that it can serve as a protective film. When the formation of the fluoroplastic protective film **28** ends, the resin film **27** may be stripped off, whereupon the unwanted areas of the fluoroplastic protective film **29** are also removed

The patterned silicon oxide film **22** is immersed in a 5 to 20 wt % aqueous potassium hydroxide solution held at 80° C. to perform etching for about 1 to 2 h. As a result, with the silicon oxide film **22** serving as a protective layer, etching goes through the single-crystal silicon substrate until it stops at the silicon oxide film **21** on the other side, to thereby form recesses **30** which serve as pressure generating chambers (FIG. **6-I**). In this step, the fluoroplastic protective film **28** effectively prevents the piezoelectric layer from being damaged by the aqueous potassium hydroxide solution.

Subsequently, those areas of the silicon oxide film **21** serving as an etching stopper which are exposed in the recesses **30** and the silicon oxide film **22** serving as an anisotropic etching pattern are stripped away with a hydrofluoric acid solution or a liquid mixture of hydrofluoric acid and ammonia. Finally, the fluoroplastic film **26** (**28**) is etched away with an oxygen plasma (FIG **6-II**).

If desired, the etching may be performed in such a way that windows **31** are formed in at least those areas of the fluoroplastic film **26** (**28**) on top of the conductive layer **25** serving as the upper electrode which provide connections to the conductor pattern whereas the resin film **26** (**28**) remains intact on the lateral sides of the piezoelectric layer **24** In this